QUESTIONS AND ANSWERS ON NANOBUBBLE STORAGE
Compiled from answers given by inventor Udo von Wimmersperg (deceased)
January 8, 2010

1. Question: *Is the proposed technology a method for making and storing fuels such as hydrogen and methane?*

Response: The process is applicable to the storage of gases in the form of a dispersion of nanometer scale bubbles in water. Of particular interest is the storage of hydrogen, and also methane.

2. Question: *Is coalescence of the nanobubbles a problem, once they are created?*

Response: It is not expected to lead to significant gas losses. In the case of small bubbles this effect is suppressed due to large surface to mass ratios. In particular gravitational aggregation plays a negligible role. Experimental observations by others have shown that nanometer scale bubbles are indefinitely stable. A technical publication on this is available. In particular, it was observed that aggregates of such bubbles survive in contact with each other as well as with macroscopic interfaces.

3. Question: *Are gas bubbles in liquid fuels anticipated?*

Response: While it is conceivable, the invention is not directed at forming gas bubble dispersions in liquid fuels. Water is considered the best and primary liquid for this purpose. It should also be noted that the surface tension of water at interfaces with sparingly soluble gases, such as hydrogen and methane, is negligibly affected by the choice of gas to be stored.

4. Question: *What is the container pressure required to prevent surface evaporation considering that saturation will occur when the partial pressure of hydrogen reaches the bubble pressure?*

Response: The container need only be at ambient pressure, for which the calculated solubilities hold. Saturation with gas at this pressure ensures that gas is not transported by dissolution. This should not be confused with a separate effect, namely the permeability of the bubble skin to gas.

5. Question: *How is the gas released?*

Response: The method used to release gas from the aqueous dispersion depends on the application. In the case of an internal combustion engine one might choose to inject the dispersion into the inlet manifold and carry the water through the combustion and expansion process. Alternatively, the gas can be separated by weakening the surface tension of the water through raising the temperature of the dispersion. This can be done, for example, by utilizing waste heat. Another method to release hydrogen would be to introduce an additive that lowers surface tension. The rate at which gas separation from liquid can be effected is related to prevention of foaming. In the case of fuel cells, it may be advantageous to introduce the gas in dispersion.

6. Question: *One can understand the theory and mechanics behind nano-bubbles but this doesn't explain they can be formed.*

Response: The essential requirement for bubble formation of a particular size is to control the mass of gas that is to be encapsulated. Methods to do this are discussed in the patent application.

7. Question: *Please explain how the surface tension of a bubble has the energy to hold back 3,000 atm of pressure.*

Response: It is not energy that can be called upon to enclose gas at pressure but the force exerted by surface tension. For dimensions of the scale of nanometers, deviations from bulk phenomena do occur due to finite molecular size. For that reason, there is a lower limit to bubble size; this occurs around diameters of one nanometer. Another important consequence of finite molecular size is that in such small bubbles a large fraction of the gas molecules is at the surface; in bulk volumes this fraction is negligible.

8. Question: *Please explain how volumetric and gravimetric energy densities are derived. The indicated energy densities would suggest a fluid density approximately 5 times greater than liquid hydrogen. This seems inconsistent with physical properties of hydrogen.*

Response: The quoted energy densities result from a model calculation in which bubbles of radius 0.95 nanometers contain 263 hydrogen molecules in a cage of 193 water molecules. This configuration is expected to be close to the limit of the smallest viable bubble. At maximum concentration, 15% of the volume is occupied by water, and the resulting dispersion has a density of about 360 grams per liter. Backing away somewhat from the concentration limit, the volumetric energy content of these dispersions are expected to be comparable with gasoline, with the gravimetric energy content being around twice that of gasoline. The absence of phase boundaries above the critical temperature (33 K for hydrogen) is also noted. For this reason, the properties of the liquid state of hydrogen do not play a role in the temperature range of the processes in question.

9. Question: *Please explain the apparent contradiction regarding when bulk properties apply because on the one hand Henry's Law of solubility does not apply due to the affinity of the gas molecules to the bubble wall surface relative to the free molecules and yet the compressibility of the hydrogen approaches an ideal gas. It is agreed that nano physics may be somewhere between "bulk" theory and molecular theory but it is not clear what theory is used.*

Response: One must distinguish issues about the solubility of the gas in water from the solubility limit of the gas in water outside the bubbles at ambient pressure. Once the solubility limit is attained in the water, then thereafter, no further transport of gas away from the bubble can occur through the mechanism of dissolution. Henry's law does indeed apply. There is no affinity of the gas to the outside of the bubble other than that gas accumulation there constitutes renewed bubble formation. Deviations from bulk behavior at the nanometer scale are associated with finite molecular size, and with the predominance of surface effects.

10. Question: *What is the explanation as to why aggregation and coalescence would not occur?*

Response: Aggregation and coalescence do occur; what is of essence is the rate. The Stoke relation indicates that inverse sedimentation of nanometer scale bubbles in water occurs at a rate of the order of 15 micrometers per annum. At ambient temperatures, Brownian agitation limits ultimate concentration accumulations to deviations of 70 parts per million over a typical fuel tank depth of 30 cm. Stability of nanometer scale bubbles against coalescence has been observed but the mechanisms involved are not understood.

11. Question: *What is the significance of your calculation that the energy consumed by water evaporation in the combustion of the nanobubble fluid is only 1.2% of the HHV of the hydrogen being stored?*

Response: This is the fraction of energy taken up in vaporizing the water content in the dispersion when, for example, the dispersion is used directly in an internal combustion engine. The point is that the fuel efficiency is not significantly affected by the water burden.

12. Question: *How is surface tension of water addressed and controlled when it is dependent upon temperature as well as contaminants? It would seem that the size of the bubble and the resulting pressure are highly dependent on the temperature?*

Response: According to tabulations by Vargaftik, et al., the relative temperature coefficient of the surface tension of water in the range between freezing and boiling remains roughly constant at –0.2% / K. It is expected that the hydrogen dispersions will have to be stored at temperatures within this range. Contaminants, such as surfactants, do have significant influence on the surface tension of water. Additives such as anti-freeze are possible, but the subject of later experimentation.

13. Question: *Please explain why you think the fluid should be safer due to the water content?*

Response: The presence of water reduces flammability.

14. Question: *How does this invention compare with recent work with carbon nanotubes, which has been disappointing in that the quantity of hydrogen captured in the tubes has proved to be less than worthwhile to continue research? An implication here is that the energy required to "push" the gas thru the nano structure proposed for*

generation of nano bubbles may be too high to be practical. An energy balance for the production process should be conducted to further justify and evaluate the proposal.

Response: Gas flow through nanometer diameter tubes is not a practical way to produce bubbles in this size regime because the inflation pressure would have to be of the order of 3000 atmospheres. The processes we have proposed, using differential condensation or sequestration of hydrogen in porous surfaces, take place at 3 atmospheres. Subsequent compression is done by surface tension, using up thermal energy. The overall energy investment in pressurizing the bubbles and constructing the surface area amounts to 0.83% and 1.17% respectively of the hydrogen energy content of the dispersion. This energy is recouped as part of the total energy yield.

15. Question: *How do you envision the end use of the "fluid," i.e. is the object to store hydrogen and then liberate it for end use or would the "fluid" be use as an end in itself?*

Response: Both avenues of utilization are possible, but it is likely that the dispersion would serve as is, including the water, in applications involving internal combustion engines, turbines and fuel cells. Alternatively, hydrogen gas can be released from the dispersion by heating, and by the addition of "contaminants."